Feature : Toward river restoration in East Asia-Pacific Region

CASE STUDY

Application of GIS and remote sensing for measuring and evaluating land-use change and its impact on water quality in the Pinang River watershed

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Ecol. Civil Eng. **6(1), 97-110, 2003.**

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Abstract: Human activities in the Pinang River watershed have dramatically changed land-use and land cover characteristics, and have subsequently altered hydrological and watershed processes. Pinang River water quality in downstream areas is badly polluted, based on the Malaysian Department of Environment-Water quality index (DOE-WQI) classification. In order to assess the past and present water quality and the possible uses of the Pinang River, a water quality index was applied to a data set collected for this study, which is based on the Malaysia DOE-WQI standards. This study investigated the land-use and land cover changes, which are the main contributors to the water quality and hydrological problems in this watershed. With some information derived from Landsat images, Geographic Information System (GIS) application and land-use/land cover map, we identified the land-use changes and landscape patterns in the Pinang River watershed. The results showed that forested and scrub areas decreased rapidly within the sub-watersheds as well as the entire watershed, in contrast to the urban or built-up areas. Statistical analysis indicates that impervious land parcels are increasing, which contribute to water pollution and watershed degradation. Based on land-use fragmentation and diversity indices, it was revealed that these indices are reliable tools for measuring and evaluating land-use and land cover changes for the general guideline for watershed management. This study revealed that integration of GIS and remote sensing (RS) data to quantify landscape structure is a feasible and efficient method for evaluating the temporal effect of land-use activities in the river basin for watershed planning and future development.

Key words: Department of Environment-Water Quality Index (DOE-WQI), Geographic Information System (GIS), Landsat TM, Land-use change, Watershed

Ecology and Civil Engineering

Introduction

Preserving the health of river basin ecosystems is a major concern in environmental watershed sustainable develop-

Received 7 October 2002; Accepted 14 July, 2003
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ment. In this study the Pinang River Basin is the focus of much recent urban development. Rapid development in the basin has threatened the quality of its rivers, especially in downstream areas. Land-use changes and water quality parameters were studied to determine its status in relation to the health of the basin ecosystem. In fact, there is a long history of such studies on land-use/land cover-water quality relationships (Roth et al. 1996; Allan et al. 1997; Johnson et al. 1997; Basnyat et al. 1999).

Land-use and land cover change can play a pivotal role in environmental changes and contribute to global change (Meyer & Turner 1991b; Dale 1997; Imbernon 1999). In this study we define land-use as human activity on the land (in sensu Turner et al. 1995). Land use is influenced by economic, cultural, political, historical, and land-tenure factors at multiple scales. Land cover refers to the surface cover on the ground as a result of the land-use: vegetation; urban infrastructure; water; bare soil or other.

Within the Malaysian context, land use planning and land use practices have significant impacts on the country's environment in general and more specifically on the state of the riverine, marine and coastal environment and resources. Many of the problems originated directly and indirectly from weaknesses in adhering to land use planning policies and procedures, particularly at state and local government levels. Since land-use and land cover are such strong determinants of water quality, methods are needed to efficiently and cost-effectively monitor regional landscape conditions (Griffith 2002). Therefore, integrated technologies of remote sensing (RS) and the geographical information system (GIS) were used to analyze the land-use changes of the Pinang River basin with its environmental deterioration, particularly the water quality index. Spatial information was acquired from RS data, while factors responsible for environmental deterioration are analyzed.

In order to assess the past and present water quality and the possible uses of the Pinang River, a WQI was applied to a data set expressly collected for this study. It is based on the Malaysian Department of Environment-Water Quality Index. Basically the water quality index (WQI), which was developed by the Malaysian Department of Environment, attempts to provide a mechanism for presenting a cumulatively derived, numerical expression, defining a certain level of water quality (Miller et al. 1986; Hambright et al. 2000; Jonnalagadda and Mhere 2001). No single parameter is sufficient to adequately express water quality. On the other hand, the enormous amount of data generated by monitoring requires some integration if the results are to be presented meaningfully to local watershed managers and decision-makers and the general public. For this reason, water quality indices have been developed, which reduce technical water quality information into a simple description of the state of water quality.

The ability to quantify landscape structure is a prerequisite for the study of landscape function and change. Landscape structure refers to the spatial pattern of distinct landscape elements, such as their size, shape, configuration, number, and type (Turner & Gardner 1991). Although landscape structures have frequently been suggested as tools for studying water quality (e.g. Jones et al. 1996), the relatively few studies that have examined them have had mixed results (Griffith 2002).

The objectives of this study are: 1) to identify landscape patterns and land-use changes in 1992, 1996 and 2000, using information derived from Landsat Thematic Mapper Images, and 2) to analyze the impact of land-use and land cover changes on WQI in the Pinang River sub-watersheds and entire watershed. The goal was achieved by using geoinformation technology, i.e. RS with the assistance of GIS and water quality data. RS techniques can be used to monitor the conversion of land cover types (Narumalani et al., 1997; Griffith 2002).

Materials and methods

Study area

Pinang River basin was the earliest urbanized and settlement area on this island, and it has experienced rapid development and landscape changes. While such developments have been great in terms of economic benefits, they have also brought about many undesired effects on the watershed environment. The highest population concentration and land-use pressures are spread along the eastern region of Penang Island, particularly in the Pinang River basin. River quality degradation in the Pinang River watershed is related to many factors and sources such as rapid urbanization, industrialization and development in the early 1990s, and these have made a significant contribution to this problem, which is related to land-use change.

The basin is located at 05°21'522" to 05°26'793" North and 100°14'429" to 100°19'701" East, and covers an area of approximately 50 km². Mean annual precipitation is 2,000 mm to 3,000 mm. In general, the western part of this basin receives the highest rainfall, due to its hilly landscape. The wet season usually occurs from May to September, due to the Southwest monsoon, but dry spells occur during the Northeast monsoon months, from November to March, where monthly rainfall is normally less than 100 mm. Often, there is no rain in January and minimum low flows typically occur during the months of the dry season. The annual average temperature is constantly high, averaging not less than 26℃. Mean annual relative humidity is high, with an average of 80%.

Based on Strahler's (1964) stream order classification, the main river system is classified as order 5. The western part of the Pinang basin is a hilly region of granite, whereas the coastal plain shows the youngest formations. These are the rather extensive tracts of Quaternary sand and clay, usually found in river valleys and coastal plains. The Quaternary deposits are alluvial, marine and mixed terrestrial-marine sediments. The topography of the watershed is divided into two main geomorphic units, the lowland flood plains and the interior hills. The terrain in the hills is usually rugged and steep, with slopes of more than 30% and elevation ranges from 300 to 800 meters above sea level. However, only 38% of the basin is forested, most of this being secondary forest with a significant proportion being illegally cleared for market gardening and orchards. Most of the natural vegetation that remains is mainly lowland *Dipterocarp* forest (<300 meter), highland *Dipterocarp* forest (≧300 meter) and scrub.

Interpretation of Landsat images and data processing

Topography maps of Penang State derived from the Department of Land and Surveys, Malaysia, with a scale of 1 : 10,000, were used to digitize the contour line, stream networks, and watershed delineation as a source of ground control points. Stream channels depicted in the topographical sheets were extracted to examine drainage information of the basin. For mapping the catchments and their boundary, the information on height provided through contours, spot heights and relative heights were used. The ridge line method was followed. These lines provide site information such as location of lowest elevated points, water divides and the highest elevation.

Patterns of land cover were studied using RS techniques based on the image analysis procedures (Fig. 1). Three Landsat 5 TM images acquired in 1992, 1996, and 2000 were selected from data available for this study. The topographic maps on a scale of 1 : 10,000 were used as a source of ground control points during the georeference process. The land-use maps on a scale of 1 : 7,500, 1 : 10,000, and 1 : 75,000 were also available and used for the study.

Data processing was performed using Erdas Imagine software 8.4, and ArcView 3.2a. For the study of urbanized watersheds, the TM images of 1992, 1996 and 2000 were specially processed to extract land cover data from the whole landsat TM scenes into three sub-scenes of corresponding years to cover the entire Pinang River watershed. A linear polynomial rectification with a nearest-neighbour resampling method was employed. This yielded acceptable average RMS errors of generally less than 0.5 pixel, which signifies an error of less than 15 m for TM imagery.

This study attempted to account for major land-use types presented in the images. The classification schema was therefore arrived at on the basis of the cover types in the study area that were present in large quantities. In addition, thorough and frequent ground checking has given detailed information about the land-use types within the basin. The land-use types within the Pinang River watershed were classified into twelve domains through coupling the unsupervised and supervised approach: 1) Residential, 2) Institutional, 3) Commercial, 4) Industrial, 5) Public utilities, 6) Recreational, 7) Cemetery, 8) Forest, 9) Agricultural, 10) Cleared/Unused land, 11) Scrub, and, 12) Mining (Fig. 2).

Water quality indices (WQI)

Five sampling sites or water quality measuring stations (WQMS) in Figure 2 were chosen because they had complete water quality data for the entire study period except for WQMS 5, which only had data for 1998, 1999 and 2000. Basin 1 represent the entire basin, while basins 2 to 5 are the sub-basins. Furthermore land use types of receiving water within this WQMS 5 sub-basin were dominated by natural forest (83%), and thus water quality conditions were less contaminated.

The WQI index was used to classify the Pinang River water quality, according to the system adopted by the Malaysian Department of Environment (Department of Environment 1994; Department of Environment 1999). Based on the WQI values range, the water quality is categorized as follows: "Clean" (WQI=81-100), "slightly polluted" (WQI =60-80) and "polluted" (WQI= 0-59). Six water quality parameters: dissolved oxygen (DO), pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (SS) and ammoniacal nitrogen (AN) from five WQMS along Pinang River networks were used to calculate this index.

This index was established based on the opinion of a panel of experts who determined the choice of parameters and weightages assigned to each chosen water quality parameter (Department of Environment 1994). Calculations are performed not on the parameters themselves, but on their sub-indices whose values are obtained from a series of equations from rating curves. The sub-indices for these parameters are named SIDO, SIBOD, SICOD, SIAN, SISS and SIpH. The formula used to calculate WQI is as follows: $WQI = 0.22 \cdot SIDO + 0.19 \cdot SIBOD + 0.16 \cdot SICOD + 0.15 \cdot SIAN + 0.16 \cdot SISS + 0.12 \cdot SIpH$, where the multipliers are the weightages for the corresponding parameters with a total

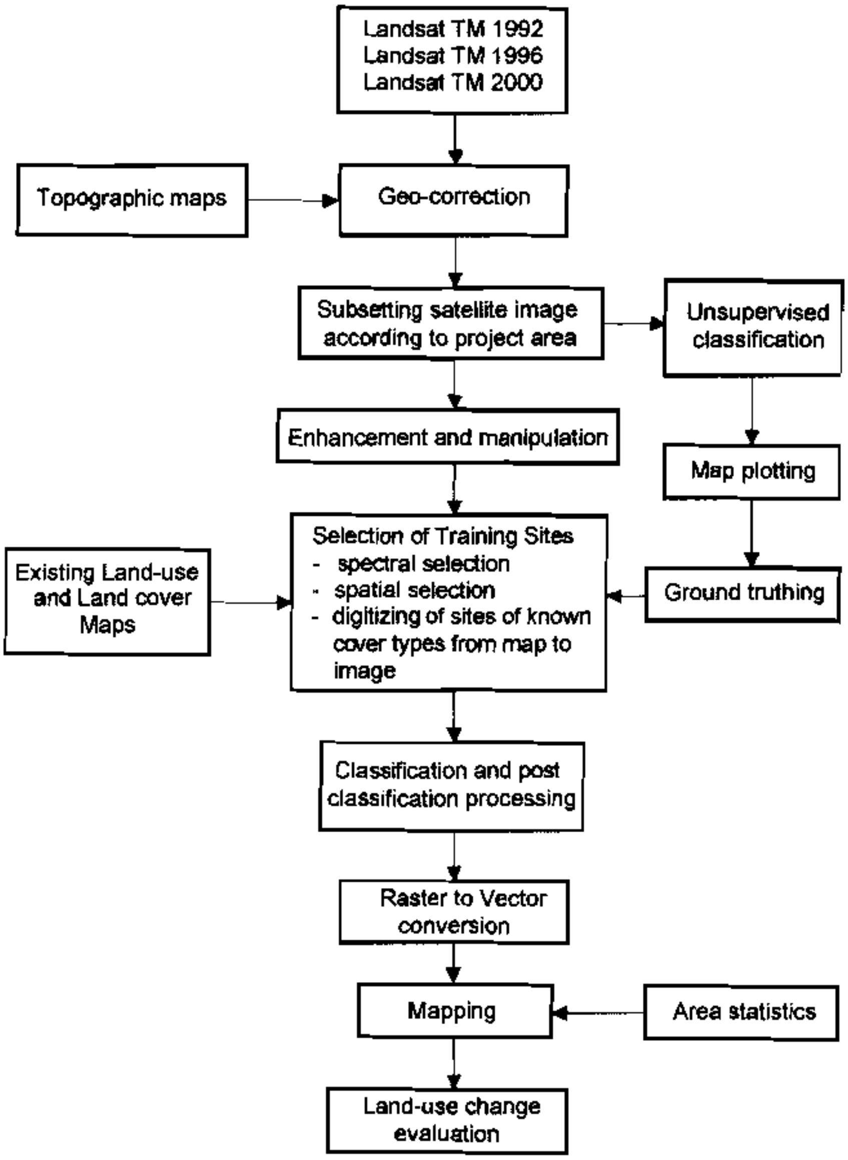

Fig. 1. Land-use and land cover data procedures.

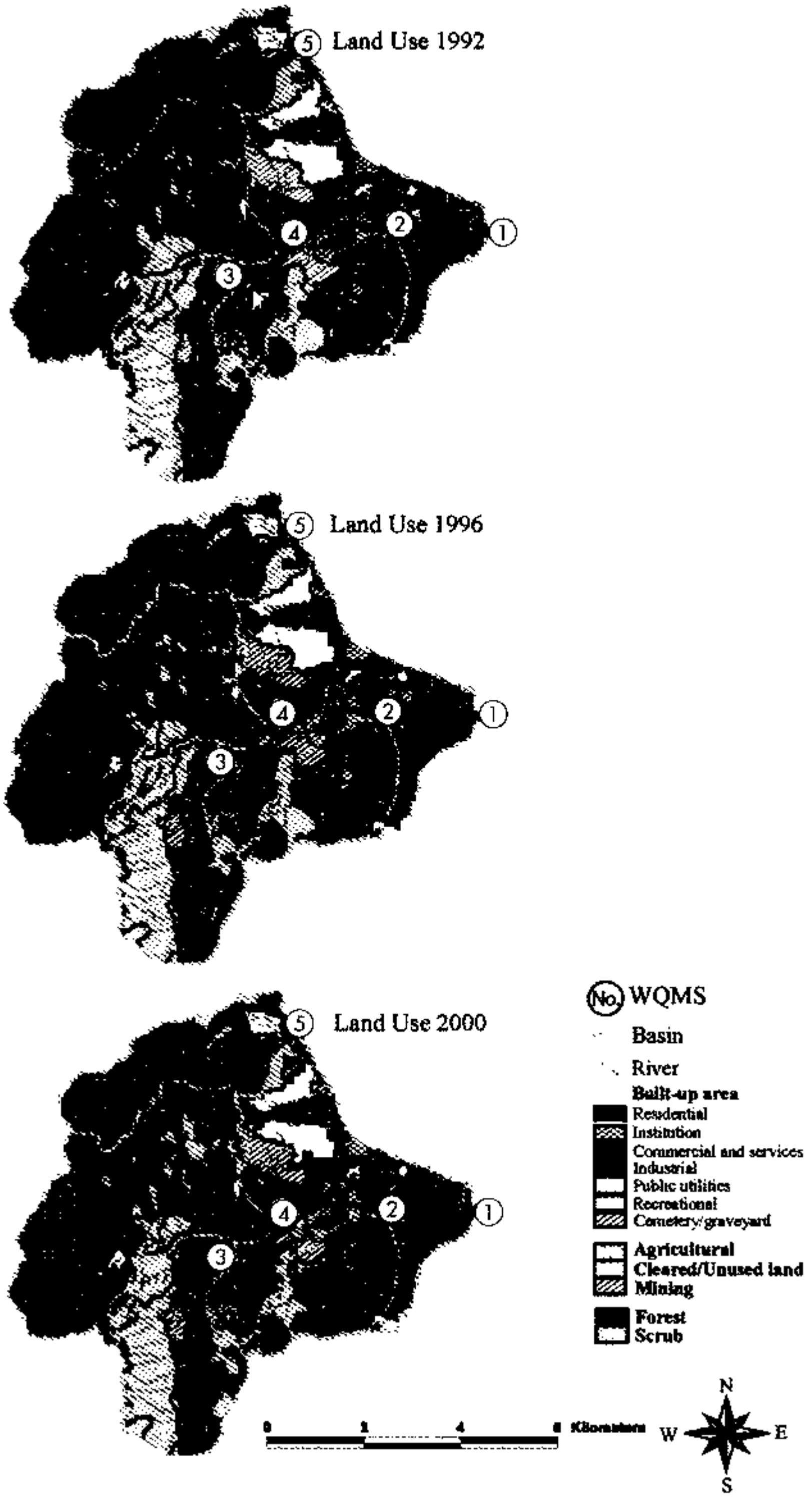

Fig. 2. Land-use distribution in Pinang River basin in 1992, 1996 and 2000. The land-use maps were derived from Landsat 5 TM and conventional land-use maps. The boundary of the map is based on the Pinang River watershed that covers an area of 50 km^2. The floodplain lies on the eastern part and the western part is hilly and rugged. The concentration of urbanized areas is on the flood plain, whereas on the hilly parts it is forested and agricultural land. The water quality samples were collected at 5 water quality measuring station (WQMS). The legend consists of sub-watersheds of WQMS, Pinang River networks and 12 land-use types.

value of 1.

Landscape pattern and statistical analysis

For comparing the landscape structure between three periods, the area, areal percentage and patch number per land-use type, were calculated using patch analysis and patch-grid analysis. Based on the Pinang River watershed land-use and land cover data, the following indicators were employed to analyze landscape change. In addition, relationships between area of land-use types in each watershed and water quality index were conducted using Pearson's correlation test.

i. Patch numbers per unit area (number of patches within 1 hectare).
ii. Mean patch area of different land-use types.
iii. Diversity index (H'): Shannon and Weaver (1949) developed diversity dominance for describing information change. It has been widely used in landscape pattern analysis (Turner et. al. 1987; Hobbs and Hueneke 1992; Baskent & Jordan, 1995; Rescia et. al. 1995; Fu & Chen 2000; Chen et. al. 2001).
iv. Fractal dimension was used to measure patch shape complexity (Mandelbrot 1982). The fractal dimension has been widely used in landscape studies (Lovejoy 1982; Fu and Chen 2000; Chen et. al. 2001).
v. The evenness index was also applied, which was derived from the Shannon Evenness Index.
vi. Landscape fragmentation index (patch number per unit area).

Results and discussion

Land-use and landscape pattern changes

To generalize the land cover classification for statistical and landscape change analysis purposes, land-use types which are related, such as residential, institution, commercial, industrial, and cemetery were re-classified into built-up areas. Within the study period, forest remained the largest land-use type in the entire basin. Most of the forest areas are forest reserves, located at the upper reaches of the river, and constitute a part of the Air Itam dam water catchments in sub-basin 4. In contrast, there are insufficient natural forests in the floodplain at the downstream and riparian areas. Removal of forest cover is known to increase streamflow as a result of reduced evapotranspiration, and also to increase peak flows as a result of the higher water table (Matheussen et al. 2000), and the lack of riparian vegetation decreased the filtering effect of non-point source pollution (Narumalani et al. 1997).

The results of using GIS to quantify the landscape structure of the sub-basins 2~5 and entire basin 1 are shown in Table. 1 and 2. According to Table 1, forest cover constituted the highest land cover in 1992, 1996 and 2000 for the whole of basin 1, and sub-basins 4 and 5. The remotely sensed data reveal that the forests have undergone deforestation during the eight-year study period. The area of forest decreased from 1,931.41 ha in 1992 to 1,851.67 ha in 1996, and to 1,806.54 ha in 2000, for the entire basin. The built-up areas domain constituted 35.78% in 1992 and increased to 38.35% in 1996 and 39.38% in year 2000. Comparatively, sub-basin 2 has the lowest forest and scrub cover among all the basins. However, the smallest land-use area was mining 13.64 ha (0.27%) where the area percentage remained unchanged in 1992, 1996 and 2000.

The total number patches in the sub-basins and the entire basin has increased substantially, particularly in the flood plain and downstream areas, which highlight the breaking up of land-use in the watershed into smaller land parcels (from 521 in 1992, to 792 in 1996, and 861 in 2000).

Table 2 shows that mean patch size for the whole of basin 1 decreased from 9.70 ha in 1992, to 6.38 ha in 1996, and to 5.86 ha in 2000. In addition, Shannon's diversity index increased from 2.52 in 1992 to 2.86 in 1996 and 2.85 in 2000 within the Pinang River watershed as well as sub-watersheds. Shannon's evenness index increased from 0.68 in 1992 to 0.76 in 1996, and 0.76 in 2000.

The patch number per unit area increased from 0.10 in 1992 to 0.16 in 1996 and 0.17 in 2000, and this reveals a rise in the landscape fragmentation index for the Pinang River watershed. The increased number of patches per unit area indicates that the landscape is highly fragmented, which provides less connectivity, greater isolation, and a higher percentage of edge area in patches.

Fractal dimension reflected changes in patch shape. High fractal dimension indicates a complex patch shape, whereas a small value implies a regular patch shape. Compared to 1992 (1.41), the fractal dimension in 2000 had decreased to 1.40 (Table 2). This implies that the existing land covers

Table 1. Area changes of land-use types from 1992 to 2000.

Basin	Land use types	1992 Area (ha)	1992 No. of Patch	1992 Percent %	1996 Area (ha)	1996 No. of Patch	1996 Percent %	2000 Area (ha)	2000 No. of Patch	2000 Percent %
1	Built-up	1807.88	372	35.78	1936.45	644	38.35	1988.18	703	39.38
	Public utilities	48.07	19	1.03	39.18	12	0.78	39.38	14	0.78
	Recreational	291.80	65	5.77	299.20	65	5.92	291.88	67	5.78
	Forest	1931.47	6	38.22	1851.67	7	36.67	1806.54	9	35.78
	Agricultural	606.39	37	12.00	548.13	45	10.86	574.68	44	11.38
	Clearland	17.13	3	0.34	3.14	2	0.06	0.94	3	0.02
	Scrub	332.93	17	6.59	357.86	15	7.09	334.02	19	6.62
	Mining	13.64	2	0.27	13.64	2	0.27	13.64	2	0.27
	Total	5049.27	521		5049.27	792		5049.27	861	
2	Built-up	376.81	59	69.18	406.86	131	74.70	410.76	140	75.42
	Public utilities	9.21	3	1.69	0.83	2	0.15	1.97	3	0.36
	Recreational	22.38	15	4.11	18.94	14	3.48	19.44	15	3.57
	Forest	31.41	3	5.77	30.81	3	5.66	30.61	4	5.63
	Agricultural	17.64	5	3.21	9.43	4	1.73	21.68	5	3.98
	Scrub	87.18	1	16.01	77.77	1	14.28	60.14	3	11.04
	Total	544.64	86		544.64	155		544.64	170	
3	Built-up	291.42	29	33.28	312.32	59	35.48	351.47	71	39.92
	Public utilities	2.49	9	0.78	3.30	5	0.37	3.35	4	0.38
	Recreational	14.78	9	1.67	14.78	9	1.68	9.82	7	1.12
	Forest	97.53	2	11.02	89.40	2	10.15	73.86	3	8.39
	Agricultural	364.33	3	41.18	351.97	5	39.98	322.75	5	36.66
	Scrub	106.82	7	12.07	108.60	6	12.34	119.16	6	13.53
	Total	880.37	59		880.37	84		880.41	96	
4	Built-up	179.87	69	11.70	196.94	112	12.81	196.91	117	12.81
	Public utilities	28.12	2	1.83	28.12	2	1.83	27.79	2	1.81
	Recreational	4.14	8	0.27	10.82	9	0.70	13.31	11	0.87
	Forest	1111.10	1	72.28	1073.85	3	69.85	1042.67	3	67.82
	Agricultural	191.51	30	12.46	165.40	38	10.76	196.53	33	12.78
	Scrub	18.02	3	1.17	57.76	4	3.76	55.67	4	3.62
	Mining	4.47	1	0.29	4.47	1	0.29	4.47	1	0.29
	Total	1537.22	114		1537.35	169		1537.35	171	
5	Built-up	6.86	8	0.98	7.14	9	1.01	7.14	9	1.01
	Public utilities	1.48	1	0.21	1.18	1	0.21	1.48	1	0.21
	Recreational	36.76	2	5.23	40.66	2	5.78	40.64	2	5.78
	Forest	589.54	1	83.85	585.38	1	83.23	585.38	1	83.24
	Agricultural	2.56	2	0.36	2.73	2	0.39	2.73	2	0.39
	Scrub	56.74	5	8.07	56.74	5	8.07	56.73	5	8.07
	Mining	9.17	1	1.30	9.17	1	1.30	9.17	1	1.30
	Total	703.13	20		703.30	21		703.27	21	

were rapidly divided into smaller land parcels or lots. More land cover types were converted into lots with simpler shapes for housing estates and commercial areas. Furthermore, the patch number per unit area increased in the entire basin and sub-basins from 1992 to 1996 and 2000, which indicates that the study area is becoming more fragmented due to diversification of land-use. Several studies have also found lower fractal dimensions in human-dominated landscapes (e.g., Turner 1990; Mladenoff et al. 1993).

Major land-use change from 1992 to 2000 is summarized in Table 3, in order to estimate and evaluate how much and what kinds of land-use types are most affected in temporal change. Forest and scrub areas have undergone rapid changes to built-up areas and agricultural land-use in all sub-basins and entire basin 1. Between 1992 and 1996, 19.40 ha of forest areas changed to agricultural land, and in addition 45.39 ha changed to being built-up areas. Land-use change from 1996 to 2000 shows more forest and scrub

Table 2. Changes of landscape patterns from 1992 to 2000.

Basin	Year	Area (ha)	NP	MP (ha)	FD	SDI	SEI	LFI
1	1992	5049.25	521	9.70	1.41	2.52	0.68	0.10
	1996		792	6.38	1.41	2.86	0.76	0.16
	2000		861	5.86	1.40	2.85	0.76	0.17
2	1992	544.64	86	6.33	1.38	2.44	0.73	0.16
	1996		155	3.51	1.39	2.72	0.78	0.28
	2000		170	3.20	1.38	2.74	0.79	0.31
3	1992	880.37	59	15.00	1.35	2.14	0.72	0.07
	1996		84	10.48	1.36	2.42	0.75	0.10
	2000		96	9.17	1.35	2.45	0.76	0.11
4	1992	1537.35	114	13.48	1.40	1.79	0.56	0.07
	1996		169	9.10	1.42	2.16	0.65	0.11
	2000		171	8.99	1.42	2.19	0.66	0.11
5	2000	703.27	21	33.49	1.39	1.47	0.67	0.03

NP-Patch Number
MPA-Mean Patch Area
FD-Fractal Dimension
SDI-Shannon's Diversity index
SEI-Shannon's Evenness index

areas being converted to agricultural land (51.88 ha) and built-up areas (41.26 ha). Sub-basins 3 and 4 show enormous change of forest areas to agricultural lands from 1992 to 2000. Moreover these sub-basins are situated at highly elevated areas.

The agricultural area consists of market gardening, mixed horticulture, orchards and poultry. Within the entire basin 1 it covered only 606.39 ha in 1992 and decreased to 548.13 ha in 1996 (Table 1). Despite this, some orchard activities and illegal farming in forested areas has led to an increase in agricultural areas in the year 2000 (574.68 ha). Such activities have been seen in sub-basin 4, where 35.12 ha and 10.82 ha of forest areas had been converted to agricultural lands in 1996 and 2000 respectively. Sub-basin 3 also shows 8.42 ha and 15.79 ha of forest and scrub areas are transformed to agricultural area. Nevertheless, the conversion of agricultural land to built-up areas (35.5 ha) from 1992 to 1996 and (35.25 ha) from 1996 to 2000 indicates urban developments are gradually replacing agricultural land due to the location at the periphery (Table 3). It should, however, be noted that the land use change from natural or cultivated areas to built-up or urbanized areas has occurred simultaneously, and it is likely that a large contribution was made by diffuse pollution derived from this land use change to the aggravate river water quality.

Water quality assessment using water quality indices

Based on Figure 3(a), six water parameters show variations and trends from 1992 to 2000 according to sampling sites. The annual average levels of DO range from 0.00 to 8.2 mg/l, and the mean variation level clearly fluctuates from 1992 to 2000. All stations show low levels of DO, despite the fact that WQMS 5 shows higher levels of annual mean DO for 2000 (8.2 mg/l), which indicates that the water quality is less contaminated, because 84% of this sub-basin is forest area. In contrast, other sub-basins and entire basins showed low levels of DO, which indicates the extent of organic pollution in aquatic systems, which adversely affect the water quality and aquatic life.

The average levels of BOD range from 1.00 to 85 mg/l. The highest levels of BOD were in 1992 and 2000 at WQMS 2 and 3, which are likely to be due to effluent from urbanized areas and agricultural activities. A rapid increases has seen in the percentage of built-up and urbanized areas (69% and 33.28% in 1992; 74.7% and 35.48% in 1996; 75.4% and 39.92% in 2000) in sub-basins 2 and 3, and effluent from such land-use types contain high oxygen demanding organic substances led to low higher levels of BOD.

Table 3. Major lanmd-use changes from 1992 to 1996 and from 1996 to 2000.

Basin	Land use types	1992-1996 Aguricultural (ha)	1992-1996 Built-up (ha)	1996-2000 Aguricultural (ha)	1996-2000 Built-up (ha)
1	Forest	19.40	45.39	30.81	2.56
	Scrub	0.30	23.60	1.07	38.70
	Cleared land		13.80		1.97
	Public utility		12.65		1.87
	Recreational		5.27		12.14
	Agricultural		35.25		35.29
2	Forest		0.61		0.30
	Scrub		9.41	0.98	18.23
	Public utility		8.38		
	Recreational		3.44		
	Agricultural		8.21		
3	Forest	8.12	0.01	15.69	0.25
	Scrub	0.30	4.39	0.10	3.19
	Public utility		3.59		0.90
	Recreational				1.96
	Agricultural		14.31		32.28
4	Forest	35.12	1.98	10.82	14.57
	Scrub		2.13		1.68
	Public utility		0.33		
	Recreational		0.11		
	Agricultural		3.00		0.98
5	Forest	0.17	0.27		0.01
	Scrub				
	Public utility				
	Recreational				
	Agricultural				

The annual average level of COD ranges from 8 to 205D mg/l. The COD level is highest at WQMS 1 to 4 in 1992. In 2000, a COD level shows slight improvement in most WQMS except WQMS 2 where showed a drastic increase from 1996. The increase in COD was attributed to the increase in organic matter due to urbanization (waste water) and industrialization.

The average level of SS, ranging from 1 to 278 mg/l, largely depends on run-off. A high level of SS is thus obtained during rainy months. Compared with 1992 and 1996, all sampling sites in 2000 show low levels of SS, and this may be related to decreases in cleared land area (Table 1). In Malaysia, very high levels of SS were recorded during rainy months. Run-off from logging, agriculture and urban areas contribute to high levels of suspended solids in Malaysian rivers (Lai & Norajiki 1988).

The average levels of pH range from 6.3 to 6.87, and high pH values were attributed to industrial pollution from surrounding areas (Wandan & Zabik 1996), while the lower values were attributed to the presence of organic matter (Gomez 1999). Unpolluted streams normally show a near neutral or slightly alkaline pH (Jonnalagadda & Mhere 2001). WQMS 4 had low pH levels in both 1996 and 2000 compared to WQMS 1, which was influenced by the high concentration of built-up areas and some industrial activities at the downstream area. However, since 1996 a decline in

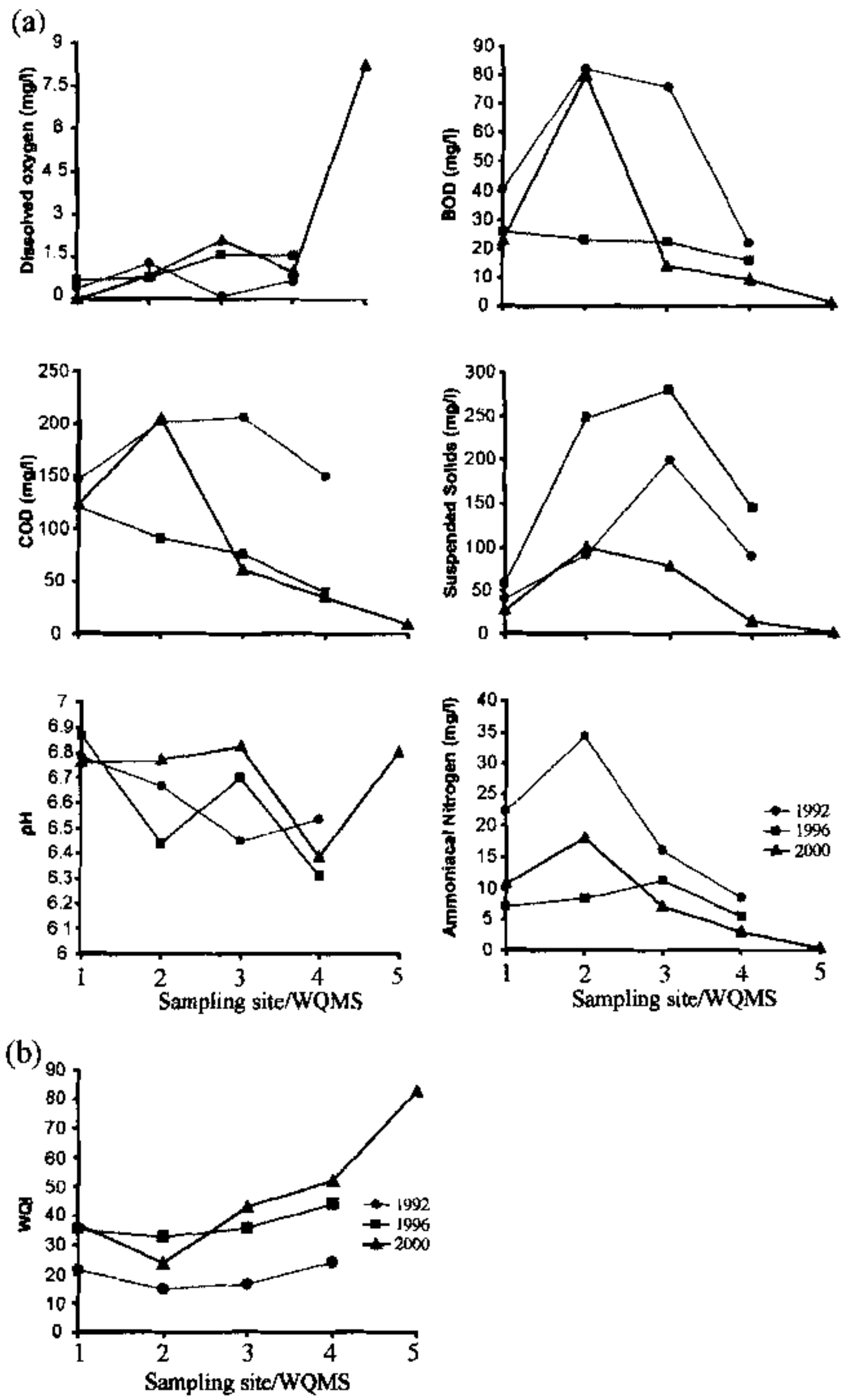

Fig. 3. Comparison of (a) DO, BOD, COD, suspended solids, pH and ammoniacal nitrogen, and (b) DOE-WQI levels for the 1992, 1996 and 2000 sampling sites within sub-watersheds and entire watersheds.

industrial activities within the Pinang watershed has lead to improved levels of pH.

AN content in river water reflects the level of pollution from domestic and animal husbandry sources. The average levels of AN for 5 sampling sites range from 0.3 to 34.3 mg/l. AN decreased in 1992, 1996 and 2000 are related to decreases in animal husbandry activities, especially pig farming, in both WQMS 3 and 4. However for WQMS 1 and 2, the AN levels decreased from 1992 to 1996 and rapidly increased in 2000, as a results of high population growth and pig farming activity. The proportion of built-up areas (73.1%) for the WQMS 2 sub-watershed is the highest among all the sub-watersheds. This is a clear indication that built-up and urbanized areas contributed to the increased of AN level. Presence of AN in a stream in an appreciable amount (<0.20 parts per million) provides strong presumptive evidence of the addition of sewage or sewage effluent (Chapman 1992; Jackson & Jackson 1996).

Figure 3(b) shows the comparison of mean annual WQI for 1992, 1996 and 2000 at the 5 sampling sites that represent sub-basins and entire basin land use types. Generally, the low water quality index indicates that the river quality at WQMS 1 to 4 was badly polluted (WQI < 59), which indicates that the water condition is not suitable for public water supply, recreation, aquatic life and navigation. Conversely, WQMS 5 shows high WQI condition and is considered clean (WQI = 83). While in 1996 and 2000, WQI at these sampling stations shows some improvement, except for WQMS 2 in 2000, the water quality is declining as aresult of 19.5 ha of forest and scrub areas being converted to built-up and agricultural areas (Table 3). According to the Malaysian Department of Environment (1994), if WQI < 59, only boating and transportation is feasible. Whereas if WQI > 80, the river conditions are acceptable for aquatic life, for water recreational activities, and for public water supply minor purification is required.

The relationship between land use and water quality index.

Mean annual WQI values for 1992, 1996 and 2000 from each station and land cover types within corresponding catchments were analyzed using Pearson's correlation. Results from the statistical analyses shown in Table 4 indicates that several land-use types were significantly correlated to water quality indices in the Pinang River watershed at a probability of < 0.05. WQI had strong positive relationships with forested areas in 1992 ($r = 0.976$), 1996 ($r = 0.930$) and 2000 ($r = 0.861$). In the case of built-up areas, WQI had strong negative relationships with 1992 ($r = -0.849$), 1996 ($r = -0.892$) and 2000 ($r = -0.911$). It is also positively correlated to scrub land and public utility land use.

These findings confirm that one of the greatest causes of water-quality problems are derived from built-up and urban land-use as a result of the increasing intensity of human activities. Runoff from different types of land use may be enriched with different kinds of contaminants (Tong & Chen 2002).

Agricultural area was not a dominant predictor for degraded water quality, as suggested by other studies (Lenat & Crawford 1994; Johnson et al. 1997), since agricultural activities are not a major activity. The results of this study suggest that using catchment landscape variables in built-up area is the most important predictor of water quality variability (see also Osborne & Wiley 1988). This relationship may have been highly influenced by point source as well as non-point source pollution that is commonly associated with residential and urbanized areas (e.g., storm water runoff). The main pollutants carried in the urban surface runoff include semi-treated and untreated domestic waste, effluent from the scattered small scales industries, and discharges from garages, petrol stations and workshops. Unlike other discharges, the control of pollution and load quantification resulting from surface runoff is much more difficult because of the diffused nature of the contributing pollution sources. After built-up areas, the three landscape factors that appeared most important in determining water quality were forested land use, scrub and public utilities. Degraded water quality, as expected, was generally negatively correlated with forested land use.

Conclusion

The impact of built-up and urban land uses on river water quality demonstrated in this study suggests that the known land-water relationship is significant enough for planners and decision-makers to pay proper attention to water-quality issues in evaluating plans and facilitating collaboration. The construction and upgrading of several municipal waste-

Table 4. Person's correlation coefficients between WQI and major land use percentages within sub-watersheds and entire watersheds

		Correlation coefficient		
Major land use types		1992	1996	2000
Built-up areas	Pearson correlation	−.849	.892	−.911*
	Sig.(1-tailed)	.151	.054	.016
	N	4	4	5
Agricultural	Pearson correlation	−.171	.007	−.261
	Sig.(1-tailed)	.829	.496	.336
	N	4	4	5
Forest land	Pearson correlation	.976*	.930*	.861*
	Sig.(1-tailed)	.024	.035	.030
	N	4	4	5
Public utility	Pearson correlation	.318	.975*	.067
	Sig.(1-tailed)	.682	.013	.457
	N	4	4	5
Recreational	Pearson correlation	.283	−.602	.260
	Sig.(1-tailed)	.717	.199	.336
	N	4	4	5
Scrub land	Pearson correlation	.993**	.918*	.294
	Sig.(1-tailed)	.007	.041	.316
	N	4	4	5

** Correlation is significant at the 0.01 level (1-tailed).
* Correlation is significant at the 0.05 level (1-tailed).

water facilities and the enforcement of effluent requirements on some industrial sources has resulted in noticeable improvements in the water quality in some of the tributaries. The major pollution sources can be classed as point and non-point. Point source pollution is derived from domestic, piggery, and industrial waste, automobile workshops and agro-based industrial waste, while non-point source are the result of rainwater suspending and carrying many different types of pollutants that settle on roofs, yards, roadways and other surfaces into receiving streams. More than 60% of the population within the Pinang River basin is served by a sewerage system, which conveys raw sewage to an open channel flume in Jelutong River for discharge into the western channel. However, about 50% of the sewered population discharges sullage water directly into public drains without any treatment, and this probably contributes to the high levels of AN in WQMS 2 (Fig. 3(a)).

Non-sewered areas in the Pinang River basin are served by various types of communal treatment facilities such as septic tanks, filter beds, activated sludge systems, rotating biological contactors and pour flush systems. According to the Malaysian Department of Environment, (1999), the existing types and number of treatment systems are 2 trickling filters; 10 activated sludges; 17 communal septic tanks with pump stations; and 26 communal septic tanks within the entire Pinang River watershed.

Insufficiency of wastewater or sewage treatment facilities and failure of local authorities to provide adequate sewage treatment facilities seem to be major threats to the Pinang River networks. According to the Penang State Veterinary Service, there are only five pig farms in the Pinang River basin with a total standing pig population of 672 heads. The estimated BOD load discharged into the Pinang River basin is 9 kg/day, based on a net loading rate of 13 g/standing pig population/day (Department of Environment-University of Malaya 1994). Furthermore the Pinang River basin is an urbanized area and per. capita water consumption is 225-liters per day (Department of Environment-University of Malaya 1994). At present, only point source pollutions are regulated by environmental agencies, such as the DOE, while non-point sources are unregulated. The results of this study show that such management may not be effective in water quality protection. The findings reinforce the notion that management of point and non-point sources should be coordinated. Such efforts should involve all levels of government, other agencies and stakeholders in a structured and focused process, since a sustainable community is interconnected with surrounding communities and the sustainability of a larger region is supported by the collaboration of these communities. Proper land-use planning within a watershed can protect water quality and reach economic goals. Watersheds are often divided into areas that are under different planning and political jurisdictions, and coordination among them is often minimal. With more studies demonstrating that the effects of human activities can and do cross-political boundaries, the development and implementation of water-quality-based watershed land-use plans should be viewed with an integrated and holistic approach.

Acknowledgements

Financial support for this work was provided by the Public Service Department of Malaysia. The authors thank the Dean and Professors of the School of Humanities, University Science Malaysia and Government Departments of Malaysia. Your support is gratefully acknowledged.

摘　要

マレーシアのピナン川流域において，人間活動による土地利用形態の変化は，特に下流域の河川水質を悪化させつつある．本研究では，ピナン川流域における土地利用変化を明らかにした上で，それが河川の水質に与えた影響を評価した．1992 年，1996 年，および 2000 年の土地利用の被覆状況をランドサットの画像データから地図化し，その経年変化を GIS を用いて把握した．そして，4つの小流域および全流域を対象に経時観測されている水質データ，およびそれをもとに算出される指標値（DOE-WQI）の経年変化を土地利用変化とあわせて検討した．なお，DOE-WQI は，マレーシア環境省によって採用されているものである．

森林や低木林の面積は経年的に急速に減少する一方，都市面積（人工造成地）が増加していること，そして，景観が分断化されてきていることが判明した．小流域および全流域の DOE-WQI の値は，それぞれの流域に含まれる森林面積と正の相関を，都市面積と負の相関を持っていた．このようなことから，流域の土地利用計画や開発計画に，リモートセンシングや GIS 技術を用いることが有効であることが確認された．

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